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Modelling the field drying of hay IV: Comparison of bulk and multi-layer models, and tests against Trawsgoed grass-wilting data

by N Thompson

1. Introduction A bulk model of swath drying which takes account of the role of equilibrium humidity in controlling the moisture flow to or from the swath time was described by Thompson (1979a). The model was later extended in order to describe vertical variations of drying rate in the swath by dividing the swath into a number of layers to each of which the concepts of the bulk model were applied (Thompson 1979b). This multi-layer model when used with a 5-day sequence of hourly weather data produced a simulation of swath drying which was in broad agreement with experience (Thompson 1980).

Comparative tests of both models have now been made, and model outputs have also been compared with experimental data from grass-wilting experiments at Trawsgoed: the results are presented here.

2. The models The multi-layer model used here is similar to that described by Thompson (1979b), but now uses a revised expression for the relation between equilibrium relative humidity (RHE), swath percentage moisture content (W, dry weight basis) and temperature (T).

$$RHE = 100\left(1 - \exp\left(-0.05W\left(1+0.017\left(T-20\right)\right)\right)\right)^{0.85} \qquad (1)$$

: this is based on the average of results found by Shepherd (1958) for swaths losing and taking up moisture, and some unpublished results for drying swaths provided by L Jones (1958).

The bulk model also uses equation (1) but is otherwise similar to that outlined by Thompson (1979a). Both bulk and multi-layer model now use the same method for determining gradients of wind, temperature and humidity above the swath, available energy and soil heat flux (Thompson 1979c); the original simplifying assumption of neutral atmospheric stability above the bulk swath is no longer therefore. The bulk swath resistance is calculated from the swath leaf resistance per unit area on the assumption that the resistances of the individual surfaces are acting in parallel: this ignores the additional resistance encountered when heat and water vapour move upwards from the bottom of the swath rather than from its top, and will tend to underestimate the bulk resistance therefore. Other factors which have been ignored and which will also increase the bulk resistance are transpiring stubble and a wet soil underlying the swath.

3. Results from the models Tests of the models were carried out using the 5-day sequence of observations at Abingdon in May 1971 and a similar set of crops variables to those used by Thompson (1980) (Table 1). One change which

Table 1 Crop variables used with Abingdon meteorological data

Swath dry weight	5 tonnes/ha
Moisture content at cutting	400% (dry basis)
Swath leaf area index	5
Green stubble leaf area index	0.5
Dead stubble leaf area index	0.5
Initial water content of dead stubble	50%
Swath water content at stomatal closure	300%
Maximum intercept per unit LAI	0.2 mm
Swath leaf resistance (closed stomata)	5000 sm^{-1}
Depth of untedded swath	0.08m
Depth of tedded swath	0.20m
Base of untedded swath	0.03m
Base of tedded swath	0.04m
Stubble height	0.05m
State of soil surface	Dry
Time of cut	0900, 14 May 1971
Number of teddings	8
Times of teddings (hours after start of simulation)	5,26,52,76,98,102,120,124

has been made to the latter is the assumption that the swath moisture content when the stomata close due to loss of tissue moisture is 300% (Harris and Tullberg 1980). The crop is assumed to be tedded a number of times but the bulk model cannot deal with the effects of tedding because it excludes vertical variations in the swath, and for this reason can only simulate a typical drying process convincingly by assuming that teddings occur very frequently. In there initial calculations the simplest possible assumption (constancy) was used in selecting a value for the swath leaf resistance after stomatal closure: the chosen value of 5000 sm^{-1} is probably typical of cuticular resistances. The use of variable values for swath resistance is discussed later. Results for both models are given in Figure 1, and also in Table 2, columns (a) and (d). Those for the multi-level model are, as expected, very similar to the results given by Thompson (1980). The calculated drying notes for the bulk model are substantially larger than those for the multi-layer model. However the bulk model is unable to account for the effects of transpiring stubble beneath the swath wind, by raising the relative humidity near the ground, reduces the rate of drying and effectively increases the bulk resistance: the assumption that the leaf resistances may be combined in parallel also underestimates the bulk resistances. Doubling the leaf resistance to 10000sm^{-1} (Table 2, column (b)) leads to drying rates generally smaller than those from the multilayer model except in the final stages on 18 and 19 May when they are larger: obviously a single value of bulk resistance is unable to reproduce exactly the drying rates given by the multilayer model although the general patterns shown by the two models are similar.

Table 2 also includes results from additional simulations using the multi-level model which explore specific aspects of haymaking. Column (e) shows swath moisture content when the swath overlies a moist, rather than a dry, soil surface. Clearly the rates of drying are usually somewhat lower when the soil is moist and therefore providing an additional source of water vapour which will raise the relative humidity within the swath. However, more detailed outputs from the model show that during the daytime a significant part of the total water vapour flux from the dry swath and stubble comes from stubble transpiration. Transpired water will become a very important factor in haymaking when, due to poor drying conditions, the swath lies in the field for more than a few days because then the stubble regrowth provides an increasingly large source of

water vapour at the ban of the swath, progressively decreasing the prospects for rapid swath drying.

The consequences of not tedding the swath are summarised in column (g), and of tedding it once only, immediately after cutting, in column (h). In the latter case the swath is deeper and less compact (Table 1) and this might be expected to enhance the drying rates. However the aerodynamic roughness of the deeper swath is larger, leading to more rapid vertical turbulent mixing within and above the swath. The aerodynamic resistances are reduced therefore, and a smaller vertical temperature is sufficient to allow the transfer of heat upwards from the swath at the same rate as in the case of a thinner, smoother swath. Thus the deeper swath is the cooler one during the daytime and this, coupled with the more effective removal of water vapour from the deeper swath, leads to similar relative humidities within each. Hence the comparatively small differences between the two final columns of Table 2 are realistic, if perhaps unexpected. The deeper, better ventilated swath does however have the advantage when intercepted water is present. Relative humidities in both swaths are then close to 100% and the important factor in drying is the maintenance of the largest possible negative gradient of specific humidity above the swath, by having the swath as deep and aerodynamically rough as possible. The consequent earlier evaporation of all surface water allows the deeper swath to become significantly drier at all levels in the subsequent few hours (eg between 0600 and 1800 on 17 May).

Results discussed up to this point have been obtained using the simplest possible assumption about leaf resistance for dry foliage (constancy throughout the drying process following stomatal closure). This implies that the effective bulk resistance for real swaths will increase in the early stages of drying as stomata close at progressively greater depths in the swath. In the later stages, when moisture content falls well below 100%, the application of the Penman-Monteith equation without regard for the increasing importance of equilibrium relative humidity would indicate an apparent increase of bulk resistance over the proper value obtained by use of the equation (Thompson 1979a)

$$\lambda E = \frac{\Delta'(R_N - G) + 1200\,\delta q'/r_a}{\Delta' + c_p(1 + r_s/r_a)/\lambda\chi} \qquad (2)$$

where

$$\chi = RHE/100$$

$$\delta q' = q_{sat}(T=T(z)) - q(z)/\chi$$

: this equation incorporates specifically the consequences of an equilibrium relative humidity less than 100%. At intermediate values of moisture content (say 80 - 250%) an analysis of experimental drying data for frequently tedded swaths using the Penman-Monteith equation might be expected to show a nearly constant bulk resistance, if the leaf resistance is constant. However if the swath is untedded the mean value of moisture content might be within the range where the equilibrium relative humidity is unimportant while at the same time the upper layers became very dry: in these circumstances the observed bulk resistance obtained from a straightforward application of Penman-Monteith would risk with decreasing moisture content. The results of Clark and McDonald (1977) for an untedded swath with no surface water showed a progressive increase of bulk resistance as the swath dried to mean moisture contents of 150%, with a moisture content in the upper part of the swath then around 100%. An analysis by Sparks (1980) of experimental data on the wilting of a number of dry,

untedded swaths showed a nearly linear relationship between bulk resistance and moisture content, down to moisture contents of less than 100%, with departures from linearity at smaller values of W which were consistent with neglect of equilibrium humidity. For reasons given already it is difficult to translate bulk resistances to equivalent leaf resistances but these results nevertheless suggest that a constant leaf resistance, independent of tissue water content, is probably unrealistic, and that an inverse proportionality to W would better represent real values. Some further support for this idea is provided by field observations on swaths and swath material by Jones (1975) which showed that, after stomatal closure the grass leaves acted effectively as wichs for the stem to which they were attached: this pathway for moisture loss from the stem presumably was less effective when the leaf moisture content became sufficiently small, and the rate of water loss from the stems was correspondingly reduced. The combined resistance of leaf and stem (referred to as "leaf" resistance throughout the present paper) would therefore show an increase as their average moisture content fell. The results of calculations made on this basis, using a leaf resistance of $7.5 \times 10^5/W$ sm^{-1} in both models, are listed in columns (c) and (f) of Table 2; the consequences of high resistance at low water content are seen as not only lower drying rates during the daytime but also a shower uptake of water at night.

4. Comparison of model outputs with experimental data Outputs of both models match in general terms the expected features of swell drying, but do not allow the selection of the most appropriate forms for the leaf and bulk resistances of the swath. Spartis' (1980) analysis is strongly in favour of an inverse relationship to W for the bulk resistance, and the results in Table 2 obtained by using this relationship in both models show a realistic sequence of drying. The set of experimental data used by Sparks may also be emploued to test the present models more rigorously. These data were obtained in experiments at ADAS Trawsgoed in which cuts of grass made at 4 or 6 week intervals were wilted for 2 days, with sampling at hourly intervals during the daytime to determine the total moisture content of the swath. Most cuts were made with a cutter-bar mower but swaths were also produced by a floil mower in a few cases. The swaths were spread uniformly over the stubble immediately after cutting but underwent no further mechanical treatments. Meteorological observations made at the experimental site were, with the exception of radiation, extracted for use in the model simulation: radiation was measured by a Gunn-Bellani integrator but since this instrument gives reasonably consistent results only over periods approaching a day the radiation values were calculated from the observed cloud amounts. The two periods selected for analysis were 30 May - 1 June 1977, a good drying spell with no surface moisture on the swath apart from dew, and 15-17 June 1977 when the swath was wet when cut and was wetted again by further rain about 24 hours later.

Model and experimental results for the first period are plotted in Figure 2: values of crop variables used in the simulations are listed in Table 3. The experimental data demonstrated the much more rapid drying of the swath produced by the float mower, showing the advantages of mechanical treatment in accelerating swath-drying, but at the same time indicating that the relation adopted for leaf resistance in the simulating must take account of factors other than straight-forward phsyiological ones such as the age of the grass when wet. The multi-layer model with a value for leaf resistance of $1.5 \times 10^6/W$ simulated the drying of grass cut by the cutter-bar mower quite clearly, but the bulk model with a somewhat larger resistance performed equally well. Neither model was able to produce results in agreement with the drying pattern of the swath from the floil mower; in each case the adjustment of the leaf resistance to match the observed drying rates on the first day resulted in final moisture contents well below those observed, apparently because the amount of water taken up by

the swath tissue at night was substantially larger than calculated. Dew was calculated to have formed on the swaths for about seven hours each night and the experimental results are also consistent with at least part of this intercepted water becoming bound in the swath, and therefore given up the following day more slowly than surface moisture. Unfortunately the results for the slower-drying wwath were not able to confirm this possibility.

Figure 3 compares measured and model values of swath moisture for the second occasion, when conditions were much less favourable for swath drying. Measurements were not made on the swath until 2 hours after it was cut, but it is estimated that the intercepted water when the swath was cut was around 3 t/ha. This value depends critically on the tissue water content at cutting: the assumed figure for the latter of 400% might have been too low since this was a second cut following only 4 weeks re-growth. However the Penman-Monteith equation intercepted water evaporates at a rate very similar to transpiration of tissue moisture when stomata are fully open, and so errors in estimates of the contribution to initial swath moisture from surface water are of little consequence in their effect on the shape of the swath drying curve. Results from the multi-layer model were in very close agreement with the experimental values, indicating that the model simulated satisfactorily interception and evaporation of rain as well as the variation with time of swath tissue moisture. The value of $1 \times 10^6/w$ sm^{-1} used for the leaf resistance in the case of the bulk model gave a slight overestimate of the rate of loss of moisture from the swath but otherwise the bulk model produced results which closely matched the observed pattern of swath drying.

Detailed results from the multi-layer model showed a substantial variation in the vertical of swath moisture content at the end of the simulations. The calculated moisture contents in the top and bottom layers on 1 June were 87 and 121 per cent, and on 17 June were 121 and 230 per cent. The wide range of values in the latter can demonstrate the importance of evaporated soil moisture in raising relative humidities at the base of swaths, and the need for tedding in less than ideal conditions in order to maintain the highest possible rate of swath drying.

5. Concluding remarks The two models which have been described provide a more rigorous framework for the analysis of field drying of hay than others presented in the literature (eg Bruch & van Elderen 1969; Firth & Lesham 1976; Hill, 1976; Clark & Mc Donald, 1977; Dyer & Brown, 1977). A major problem, however, in the effective use of the present, and previous, models is inadequate knowledge of how leaf resistance of hay varies with swath moisture content during uptake of moisture by the swath; in particular it is necessary to establish whether substantially different rates of uptake exist for all swaths with free surface moisture compared to dry swaths in a saturated atmosphere. The present assumption that resistance is the same for both drying and uptake is certainly not supported by experimental results for the drying of a lacerated swath, but the evidence on this point from the Trawsgoed swath subjected to a gentler mowing treatment is inconclusive. Further experiments are required to resolve this difficulty, with analysis of the swath samples performed to separate the contributions to total moisture from surface water and tissue moisture.

The multi-layer model was able to demonstrate the important effects of transpiring stubble, wet soil and tedding on hay drying, but the much simpler bulk model, used with a larger leaf resistance to account for these factors, reproduced closely the mean drying curve given by the more complex model. Equation (2) with appropriate values of bulk swath resistance provides therefore a theoretical framework for the analysis of historical weather records in order to provide

soundly-based estimates of days available for field hay-drying in different geographic areas. These estimates will allow sounder management decisions to be made on the choice between conservation methods such as ensiling, bann drying or field drying. The present investigation has not attempted such an analysis because of uncertainty in leaf resistance values to be used during re-wetting.

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Any comments or suggestions on this paper should be referred to the author.

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(1979b) Agricultural Memorandum 871
(1979c) Agricultural Memorandum 842
(1980) Agricultural Memorandum 886

Table 2 Swath moisture contents (percent, dry basis) with different model inputs

Date	Time (GMT)	Bulk model (a)	Bulk model (b)	Bulk model (c)	Multi-layer model (d)	Multi-layer model (e)	Multi-layer model (f)	Multi-layer model (g)	Multi-layer model (h)
14	1200	271	284	254	279;300	278;295	263;300	279;300	279;296
	1500	216	256	181	248;255	246;254	217;228	236;271	239;270
	2100	174	229	137	209;225	209;232	168;199	197;240	200;240
15	0600	174	229	137	209;211	210;232	168;174	198;232	200;226
	0900	157	219	122	199;205	203;231	158;166	185;223	190;219
	1200	112	193	88	170;177	182;190	130;137	148;199	157;199
	1500	95	183	77	154;106	167;180	117;127	132;187	141;187
16	0600	98	184	81	155;166	167;180	119;127	133;187	142;187
	1100	91	184	82	143;166	155;180	110;128	118;187	130;187
	1500	50	155	57	125;141	138;154	97;109	75;171	88;170
	2100	27	135	45	88;112	103;133	75;87	53;152	54;147
17	0600	43	133	47	86;102	103;133	74;82	55;135	59;136
	1100	52	133	50	70;103	85;133	67;83	54;136	46;137
	1500	19	108	37	49;55	69;77	57;59	26;112	21;107
	1800	16	95	33	34;44	51;64	50;53	20.93	18;90
18	0000	30	90	34	37;37	50;63	49;49	32;80	30;73
	0600	41	91	36	46;44	56;67	51;50	43;81	41;70
	1200	3	42	21	10;18	20;31	36;39	9;49	9;39
	1800	14	11	14	11;14	11;16	25;27	11;16	11;16
19	0000	31	23	17	27;24	32;36	27;28	29;26	27;25
	0600	38	29	19	34;30	41;44	29;30	36;33	34;30
	1200	5	8	14	9;15	10;19	22;25	8;13	9;16

(a) leaf resistance 5000 sm^{-1}

(b) Leaf resistance 10000 sm^{-1}

(c) Variable leaf resistance ($7.5 \times 10^5/w$)

(d) Top, bottom swath layer values:

Tedded according to Table 2.

- Leaf resistance 5000 sm^{-1}, dry soil
- Leaf resistance 5000 sm^{-1}, wet soil
- Variable leaf resistance ($7.5 \times 10^5/w$)
- Leaf resistance 5000 sm^{-1}, dry soil, untedded
- Leaf resistance 5000 sm^{-1}, tedded once at start of simulation.

Table 3 Crop variables used in simulations of Trawscoed wilting experiment.

	30/5-1/6/77	15-17/6/77
Swath dry weight (t/ha)	5.2	2.7
Moisture content at wilting (% d.b.)	400	400
Swath leaf area index	6.0	3.0
Green stubble leaf area index	1.0	0.5
Dead stubble leaf area index	1.0	0.5
Initial water content of dead stubble (% d.b)	50	50
Swath water content at stomatal closure (% d.b)	300	300
Leaf resistance (closed stomata) sm^{-1}	$7.5 \times 10^5/w$ $1.5 \times 10^6/w$ $2 \times 10^6/w$	$1 \times 10^6/w$, $1.5 \times 10^6/w$
Depth of swath (m)	0.20	0.15
Base of swath (m)	0.05	0.05
Stubble height (m)	0.08	0.08
State of soil surface	Dry	Wet
Time of cut (GMT)	1100	1000

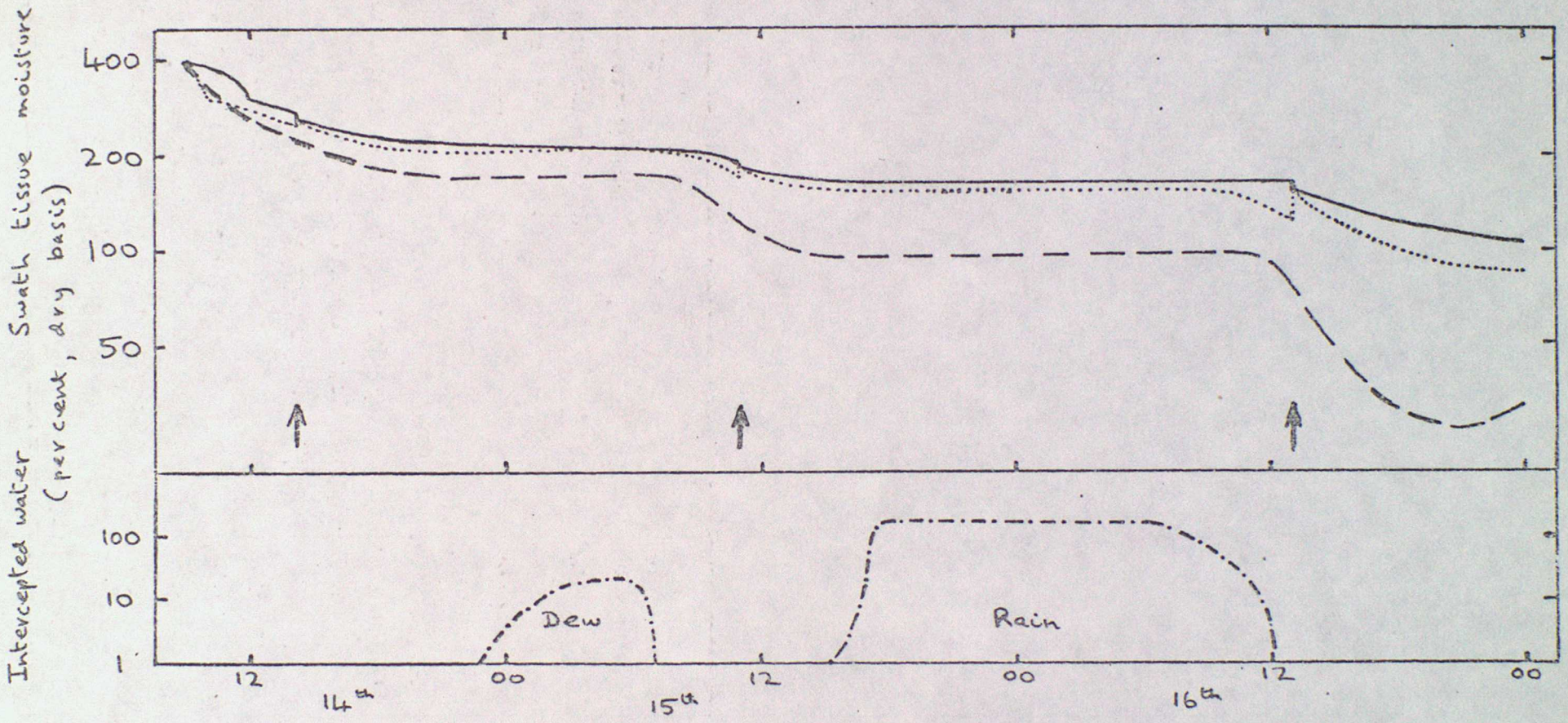

Figure 1 Simulation of a five-day sequence of swath drying, using meteorological data for Abingdon, 15–19 May 1971

.... top layer of swath

—— bottom layer of swath

-- bulk model

-.- swath surface moisture, multi-layer model (similar values were found using bulk model)

(vertical arrows show teedings)

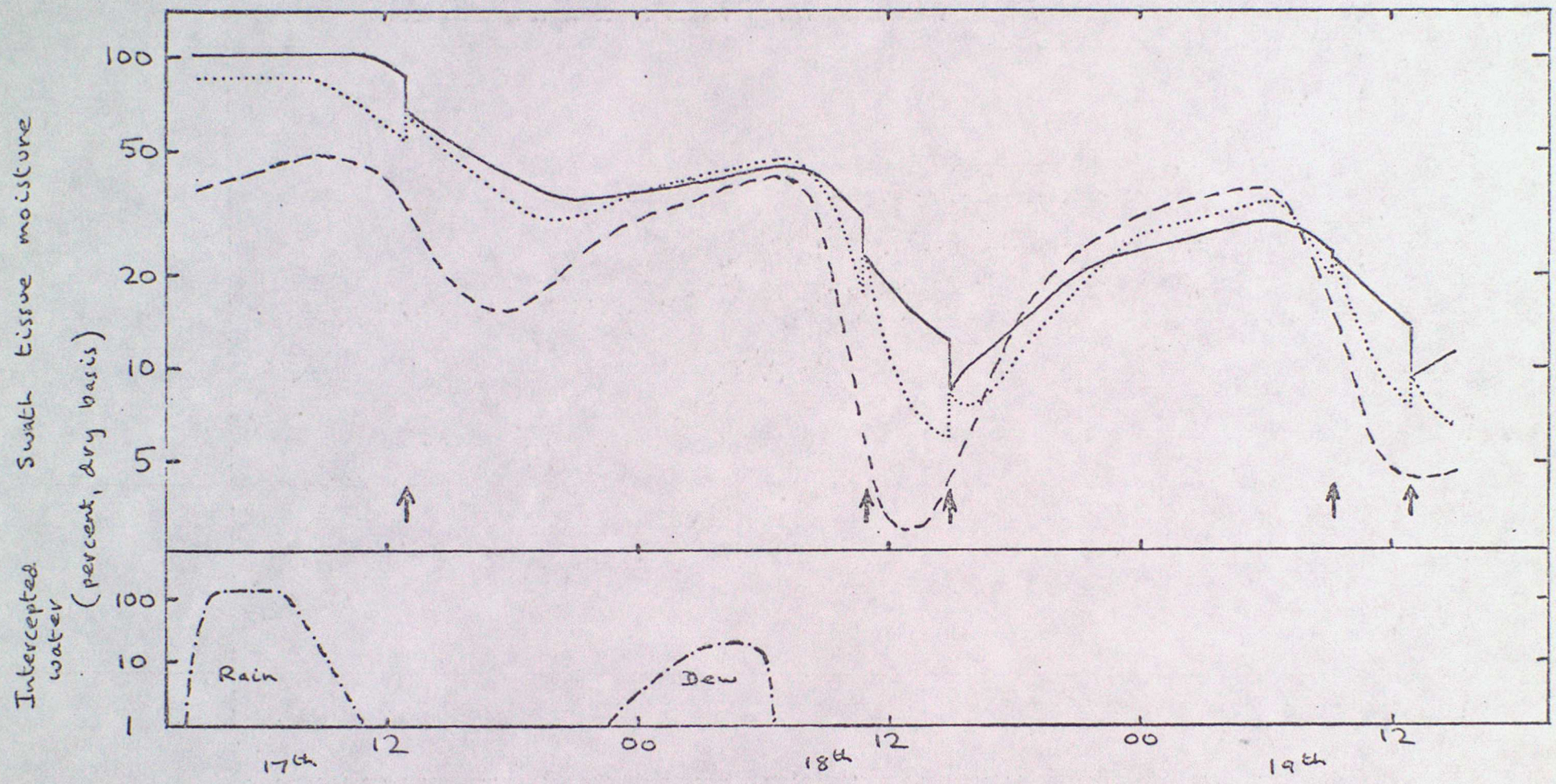

Figure 1 (continued)

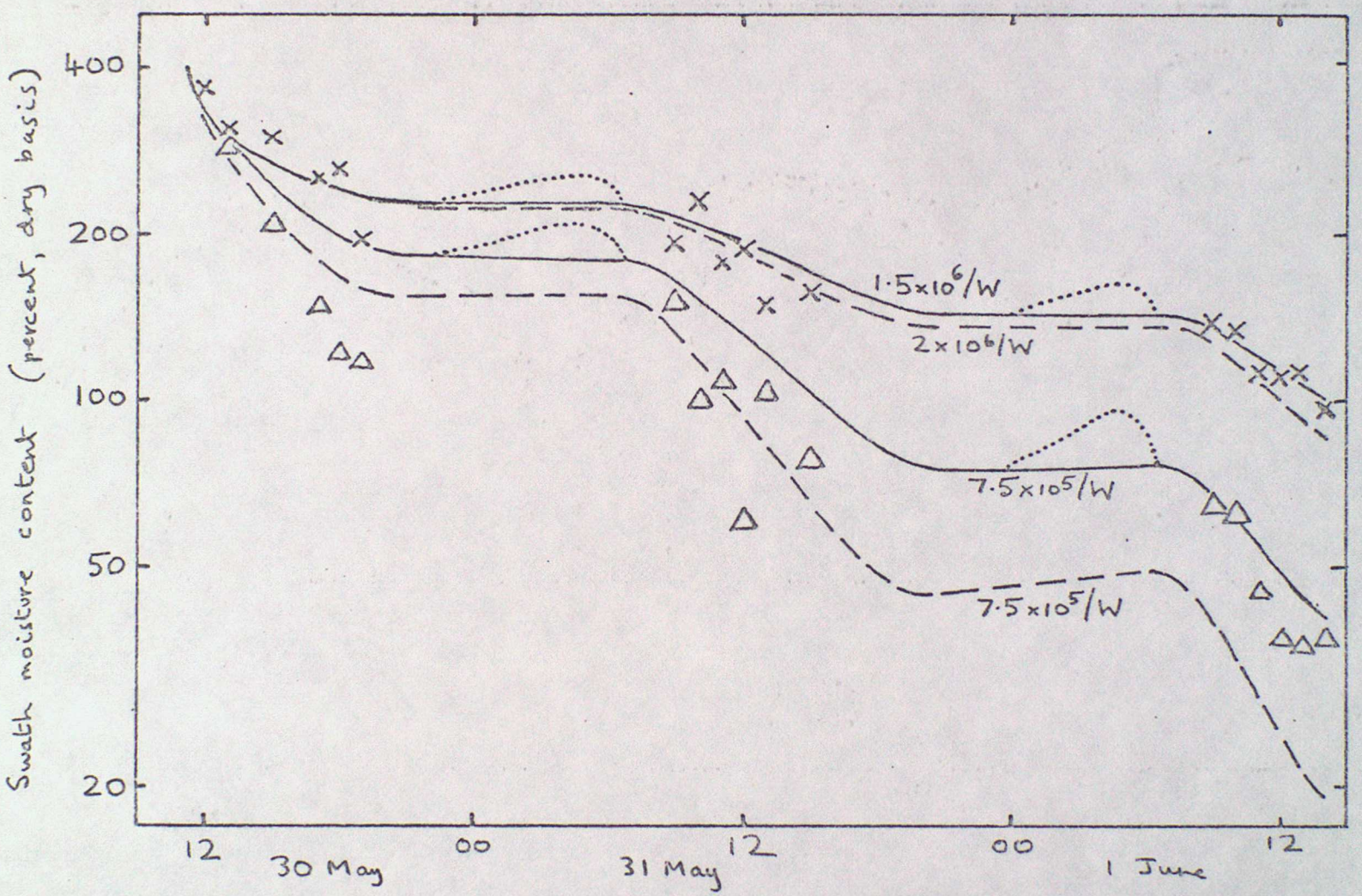

Figure 2 Simulated and measured swath moisture 30 May – 1 June 1977

× measured, cutter-bar mower

△ measured, flail mower

— mean tissue moisture content from multi-layer model

···· intercepted water, multi-layer model

– – tissue moisture content from bulk model (intercepted water was similar to that calculated by multi-level model)

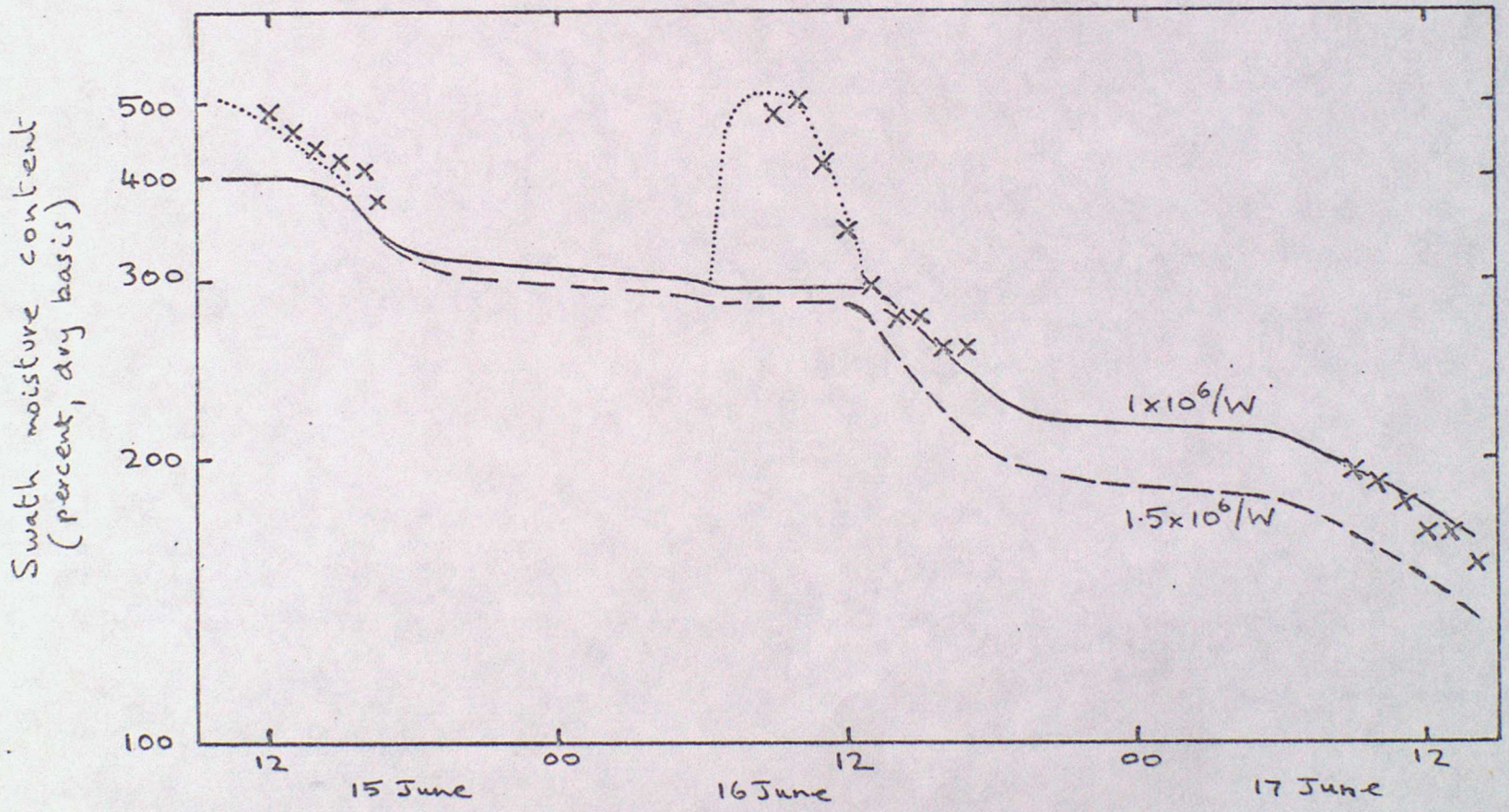

Figure 3 Simulated and measured swath moisture 15–17 June 1977
(explanation of symbols is given in Figure 2)